A Complete Survey of the Transient Radio Sky and Implications for Gamma-Ray Bursts, Supernovae, and other Relativistic Explosions

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ABSTRACT

We had previously reported on a survey for radio transients, conducted by comparing the FIRST and NVSS radio catalogs, and resulting in the discovery of nine possible sources. These were used to set an upper limit on the number

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of orphan gamma-ray burst (GRB) radio afterglows, and thus a lower limit on the typical GRB beaming factor ($f_b^{-1} \equiv (\theta_{jet}^2/2)^{-1}$). Here we report radio and optical follow-up observations of all of these possible transients, achieving the first full characterization of the transient radio sky. We find that seven source are unlikely to be real radio transients. Of the remaining two sources, one is most probably an optically obscured radio supernova (SN) in the nearby galaxy NGC 4216, the first such event to be discovered by a wide-field radio survey. The second source appears not to be associated with a bright host galaxy (to a limit of $R < 24.5$ mag). Too radio luminous to be associated with a GRB, we speculate that this may be a flare from a peculiar, variable, radio-loud active galactic nucleus, or a burst from an unusual Galactic compact object, but its exact nature remains a mystery and merits further study. We place an upper limit of 65 radio transients above 6 mJy over the entire sky at the 95% confidence level. The implications are as follows. First, following the analysis in our previous paper, we derive a limit on the typical beaming of GRBs; we find $f_b^{-1} \gtrsim 60$, ~ 5 times higher than our earlier results. Modifying our model parameters and analysis scheme leads to values which are likely to be within an order of magnitude from this number. Second, our results impose an upper limit on the rate of events that eject $\gtrsim 10^{51}$ erg in unconfined relativistic ejecta, such as conical jets, whether or not accompanied by detectable emission in wavebands other than the radio. Our estimated rate, $\dot{n} \leq 1000$ yr^{-1} Gpc^{-1}, is about two orders of magnitude smaller than the rate of core-collapse SNe (and type Ib/c events in particular), indicating that only a minority of such events eject significant amounts of relativistic material, which are required by fireball models of long-soft GRBs. Finally, we consider the prospects of future radio surveys. We show that future wider and/or deeper radio variability surveys are expected to detect numerous orphan radio GRB afterglows. Furthermore, the fact that our survey probably detected an optically obscured radio SN illustrates the great potential of sensitive surveys with new radio instruments to revolutionize the study of nearby SNe.

Subject headings: supernovae: general — gamma rays: bursts

1. Introduction

Exploring the time domain with wide-field surveys, covering significant parts of the sky, is one of the promising new frontiers in observational astronomy. This area has been little

explored so far, mostly due to the technical difficulty in conducting multi-epoch deep surveys which cover wide areas of sky. Opening this new window of discovery is one of the main objectives of new, large optical surveys, like the Palomar QUEST Survey (Djorgovski et al. 2004) and the Supernova Legacy Survey (SNLS, Sullivan et al. 2004), and is a major science driver for more ambitious forthcoming initiatives such as Pan-STARRs (Kaiser 2004), the Large Synoptic Survey Telescope (LSST, Claver et al. 2004), and the SuperNova Acceleration Probe (SNAP, e.g., Linder et al. 2004). Initiatives in the radio band include the Allen Telescope Array (ATA) and the Square Kilometer Array (SKA, Carilli & Rawlings 2004). Some initial results from the above-mentioned optical surveys are already emerging (e.g., QUEST, Mahabal et al. 2004; and SNLS, Sullivan et al. 2004), and some relevant studies are also being conducted using the Sloan Digital Sky Survey (SDSS; e.g., Lee et al. 2003) even though, by design, this survey invests few resources in exploring the time domain.

Large parts of the high-energy (gamma-ray and X-ray) sky have been almost continuously monitored for variability in the last decades, by dedicated space missions such as the Rossi X-ray Timing Explorer, the BATSE instrument on board the Compton Gamma-Ray Observatory, and the interplanetary network (Hurley et al. 2002), but this wide-field monitoring is conducted by low-resolution instruments (typically worse than $1'$), making the discovered transients difficult to localize. While higher-resolution X-ray imaging is possible with instruments on board *Swift*, *Chandra*, and *XMM-Newton*, the limited field of view and long exposures required for imaging faint sources makes sensitive, high-resolution, wide-field surveys in these bands impractical (although see Read et al. 2004).

In the radio band, wide-field surveys covering most of the sky have been carried out. While not originally designed for variability studies, these surveys do offer the opportunity to explore the time domain over a significant part of the sky, with reasonable sensitivity (a few mJy) and at decent resolution (significantly better than $1'$). Indeed, in Levinson et al. (2002, hereafter Paper I) we carried out such an analysis by comparing two wide-field surveys conducted with the Very Large Array (VLA) – the "Faint Images of the Radio Sky at Twenty centimeters" survey (FIRST, White et al. 1997) and the NRAO VLA Sky Survey (NVSS, Condon et al. 1998) – in search of transient sources.

That study was motivated by the search for a specific phenomenon, the so-called "orphan" afterglows of cosmological gamma-ray bursts (GRBs; e.g., Rhoads 1997). If the radiation associated with a GRB is beamed (i.e., emitted into a small solid angle) it follows that we do not observe many such events whose radiation is beamed away from us. At late times, the emitting material decelerates and the lower-energy afterglow emission from such GRBs (e.g., in the radio), becomes isotropic, and therefore observable (see Paper I for more details). We thus expect "orphan" GRB radio afterglows to appear as transient radio

sources which are not related to any observed GRB. Our survey revealed nine possible radio transients, and in Paper I we used this to investigate the typical beaming of GRBs.

Here, we report the results of a follow-up effort that leads to the full characterization of this sample, and thus of the transient radio sky. A plan of the paper follows. We describe radio and optical follow-up observations of the candidate radio transients from Paper I in § 2. In section § 3 we report on the properties of the two real transient sources we discovered, a probable radio dupernova (SN) in a nearby galaxy and a source with no optical counterpart which we show is unlikely to be associated with a GRB. In § 4 we discuss the main implications of our work, including an improved limit on the typical beaming of GRBs (§ 4.1), and a limit on the total rate of nearby relativistic explosions, which implies that most core-collapse SNe do not eject unconfined relativistic outflows (§ 4.2). We also take a broader approach, and discuss the implications of our findings in the context of current and future wide-field variability surveys in (§ 4.3), and summarize our results in (§ 4.4).

2. Observations

2.1. VLA Follow-Up of the Radio Transient Candidates

Following the discovery of nine candidate radio transients in the survey described in Paper I, we launched a follow-up program with the Very Large Array (VLA[1]) at both 1.43 GHz and 8.46 GHz. The initial observations toward all nine sources were taken in 2002 May and 2002 November with the VLA in the BnA, B, and C array configurations – matching the resolution of the FIRST survey. The integration times were chosen so that any bona fide orphan afterglow candidates could be detected on the basis of their power-law decline. Dual-frequency observations were used to obtain some spectral discrimination for identifying variable, flat-spectrum active galactic nuclei (AGNs). The data were reduced with the Astronomical Image Processing Software (AIPS) in the standard manner. In Table 1 we present a summary of the available radio observations for each of these candidates. For one source (#4 in Table 1.; VLA 121550.2+130654) we made additional flux-density observations and re-analyzed available archival data. These data are summarized in Table 2; see § 2.2 for more details.

Of the nine objects identified in Paper I, we find that five are unlikely to be variable at all. Of these, two (#1 and #3 in Table 1) are constant sources whose flux measurements were

[1]The VLA is operated by the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

compromised by side lobes from nearby bright sources (flux ≥ 1 Jy). Two others (#2 and #7 in Table 1) are constant sources that were not properly deblended from neighboring objects in the lower-resolution NVSS survey. The final false candidate (#6 in Table 1) appears to be an image artifact of an unexplained nature in the FIRST catalog.

Of the remaining four candidates, two are variable sources whose nature is of little interest to our current survey. VLA122532.6+122501 (#5 in Table 1) is a radio-variable, flat-spectrum source ($\alpha = -0.16$) projected on the nucleus of a nearby galaxy (VPC 418; $R \approx 16$ mag; Young & Currie 1998), and thus most likely an AGN. VLA165203.1+265140 (#8 in Table 1) is coincident with the known pulsar PSR J1652+2651.

The last two sources are interesting, and remain viable radio transient candidates. VLA121550.2+130654 (#4 in Table 1) is a non-nuclear steep-spectrum source in the nearby galaxy NGC 4216. This source continued to brighten, then peaked during our observations, and Figure 1 shows the light curve compiled from all available data. Our modelling (e.g., Soderberg, Nakar, & Kulkarni 2005a) shows that the location and light curve of this radio transient are consistent with it being a sub-relativistic Type II supernova (SN II) in NGC 4216, but they are also consistent with the relativistic ejecta resulting from an off-axis GRB. Very Long Baseline Array (VLBA) observations designed to measure the spatial size of the remnant and thus deduce the speed of the ejecta, discriminating between these two classes of stellar explosions, are described in the next section.

VLA172059.9+385227 (#9 in Table 1) was clearly detected (with a flux of 9.4 ± 0.2 mJy) in a FIRST survey image obtained in August 1994 (detection limit ~ 1 mJy), but is absent from an NVSS image obtained in April 1995 with comparable sensitivity, as well as in our subsequent imaging during 2002. Thus, this source appears to be a truly transient radio source. The absence of a bright host galaxy disfavors a radio SN identification for this source, but it remains a viable GRB radio afterglow candidate. Below we explore this further using deep imaging of the location of VLA172059.9+385227.

2.2. Investigation of VLA121550.2+130654

2.2.1. VLBA Observations of VLA121550.2+130654

To measure the size of the radio source, we obtained an 8-hr VLBA observation of VLA121550.2+130654 on 2004 May 2 UT. The observation was taken in standard continuum mode with a bandwidth of 4×8 MHz centered on observing frequencies of 1.4 and 8.5 GHz. Fringe calibrations were applied using 3C286 and phase referencing was conducted using J1207+1211 at an angular distance of 2.3° from the radio transient.

We detect the source at a position of $\alpha = 12^{\rm h}15^{\rm m}50^{\rm s}.235$, $\delta = +13°06'54''.03$ (ICRS J2000.0) with a positional uncertainty of 10 mas in each coordinate (Figure 2). We note that these errors are dominated by the positional uncertainty of J1207+1211. Using the VLBA utilities within AIPS, we find a flux density for the transient of $F_{\nu,1.4~\rm GHz} = 9.63 \pm 0.40$ mJy and $F_{\nu,8.5~\rm GHz} = 2.45 \pm 0.55$ mJy. Both 1.4 GHz and 8.5 GHz detections are essentially unresolved within the beams, 9.53 mas $\times$ 4.91 mas at 1.4 GHz and 1.82 mas $\times$ 0.91 mas at 8.5 GHz. Analysis by VLBA custom software including circular and elliptical Gaussian fits to the data result in 3σ upper limits on the source diameter of 2.9(4.5) mas at 1.4 GHz, and 3.4(4.0) mas at 8.5 GHz for circular (elliptical) Gaussian models, respectively (M. Bietenholz, 2005, private communication). We note that there is no emission from the host galaxy at this resolution.

2.2.2. Optical Monitoring of NGC 4216, Host Galaxy of VLA121550.2+130654

In order to detect, or set limits on, any optical emission coincident with the emergence of this radio source, we have examined optical images of NGC 4216, obtained between the years 1991 and 2004. We retrieved images obtained by the 48-inch (as part of the second Palomar sky survey, POSS-II) and 60-inch telescopes at Palomar Observatory from the NASA Extragalactic Database (NED)[2], and images obtained at the JKT telescope at La Palma from the ING archive[3]. We have also re-examined numerous images obtained by the Lick Observatory Supernova Search utilizing the 30-inch Katzman Automatic Imaging Telescope (KAIT; Li et al. 2000; Filippenko et al. 2001; Filippenko 2005) at Lick Observatory, between April 1997 and May 2004. All these images reach comparable depth ($\sim$ 19 mag) and do not show a compact source at the radio position of VLA121550.2+130654. Some of the best KAIT data were also intercompared using the CPM image subtraction method (e.g., Gal-Yam et al. 2004), and we detect no variable optical source at the radio location down to the KAIT detection limit, typically $R = 19.5$ mag.

2.3. Optical Follow-Up of VLA172059.9+385227

As reported in Paper I, inspection of Palomar Digital Sky Survey plate data covering the location of VLA172059.9+385227 did not reveal any candidate host galaxies of this event.

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[2]The NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

[3]http://archive.ast.cam.ac.uk/ingarch/ .

We have therefore obtained deeper optical imaging using the Palomar Observatory 200-inch telescope (P200; R band) and the Keck-I 10-m telescope (I and g bands).

Photometric calibration of this field, using Landolt (1983) standard stars, was obtained under photometric conditions with the Wise Observatory 1-m telescope. Six secondary calibrators in the vicinity of VLA172059.9+385227 were measured, with typical magnitudes of 19 (in the R band). However, as these stars were saturated in our deeper Keck and P200 images, additional, intermediate-depth images were collected with the robotic 60-inch telescope at Palomar (Cenko et al. 2005, in prep.), and used to place unsaturated objects in our deep images on the zero points defined by the Wise calibration. An observing log is given in Table 3.

3. Results

3.1. VLA121550.2+130654: a Likely Radio Supernova in NGC 4216

Figure 1 and Table 2 show the radio (1.4 GHz) light curve of this source. We find that its overall characteristics are consistent with those of a Type II SN (see Weiler et al. 2002 for a review). In particular, the temporal evolution and the steep spectral index are consistent with those measured for the radio-luminous Type II SN 1979C (Weiler et al. 1991). To illustrate this, plotted in red (dashed curve) in Figure 1 is a continuous model curve which has been shown by Weiler et al. (1991) to describe the 1.4 GHz observations of SN 1979C very well. The plotted curve is shifted in time and scaled in flux to best fit the data, but the shape of the curve is kept constant (i.e., we applied no “stretch” correction). As can be seen, this curve describes our data quite well. While some Type Ic SNe are also radio bright (e.g., SN 1998bw, Kulkarni et al. 1998; SN 2003L, Soderberg et al. 2004), their light curves evolve quickly and are inconsistent with our data, as demonstrated by the cyan (solid) curve in Figure 1, representing the radio light curve of SN 1998bw from Kulkarni et al. (1998) scaled in flux and time as above. This light curve needs to be “stretched” by a factor of ~ 50 in order to match the temporal evolution of VLA121550.2+130654.

NGC 4216 is a member of the Virgo cluster of galaxies. Assuming a distance of 15.9 Mpc to the Virgo cluster (Graham et al. 1999), the peak flux of this event was $\sim 2.7 \times 10^{27}$ erg s^{-1} Hz^{-1}, also typical of known radio SNe (Weiler et al. 2002).

At the bottom of Figure 1 we mark the periods of time in which a bright optical SN in NGC 4216 would have been visible in the archival images we have collected (§ 2.2.2). The black arrows mark the actual dates of observations. The horizontal line is our estimate for the range of dates in which an unobscured SN with peak optical luminosity and light-curve shape

similar to those of SN 2002ap (e.g., Gal-Yam, Ofek, & Shemmer 2002; Foley et al. 2003), and which would have been visible in these archival data, would reach peak brightness. In other words, SNe whose peak brightness occurred typically between 250 days before and 10 days after each observation would have been detected in these images. Optically luminous SNe with broader light curves (e.g., radio-bright events like SN 1979C, SN 1998S, and SN 1998bw) would have been visible for even longer periods of time. The fact that we do not detect an optical counterpart to VLA121550.2+130654 in any of the images we inspected, combined with the effectively continuous monitoring of this galaxy in the last decade, suggests that this event was probably heavily obscured by dust.

3.1.1. Angular Size of the Radio Ejecta

If VLA121550.2+130654 is a Type II supernova, then we can estimate its expected angular diameter by comparing it with other well-studied supernovae. We chose to compare it with SN 1979C since both objects are of comparable brightness, and the host galaxy of SN 1979C (M100) and the host galaxy of VLA121550.2+130654 (NGC 4216) both lie in the Virgo cluster. VLBI measurements by Bartel & Bietenholz (2003) taken from 3.7 to 22 years after the explosion of SN 1979C show an almost free expansion over this time. Adopting their best-fit parameters, the expected angular diameter for an isotropic expansion is θ=2.1 ($t_{\rm years}$/7.0) mas.

In contrast, if VLA121550.2+130654 is a GRB we estimate its angular diameter (Frail, Waxman, & Kulkarni 2000) at the distance of NGC 4216 to be $\theta = 17\,(E_{51}/n_\circ)^{1/5}(t_{\rm years}/7.0)$ mas, where E_{51} is the kinetic energy of the shock and $n_\circ$ is the density of the circumburst medium. This estimate assumes an isotropic outflow expanding non-relativistically (i.e. Sedov-Taylor dynamics). In reality, during the early phase (t < 0.5 yrs) the GRB outflow expands relativistically and the geometry is probably jet-like. More detailed calculations for the size evolution of GRB jets for different viewing angles is given in Granot & Loeb (2003). Note that both SN and GRB explosions release about 10^{51} erg of kinetic energy but the first drives a slow shock ($v_s \approx 5000$ km s^{-1}), while the other drives a shock that is initially relativistic ($v_s \approx c$).

In the case of VLA121550.2+130654, our upper limits on the angular size are consistent with the size expected from scaling the observations of SN 1979C, but are in strong conflict with the predictions from GRB models. We therefore conclude that VLA121550.2+130654 was a radio-selected Type II supernova.

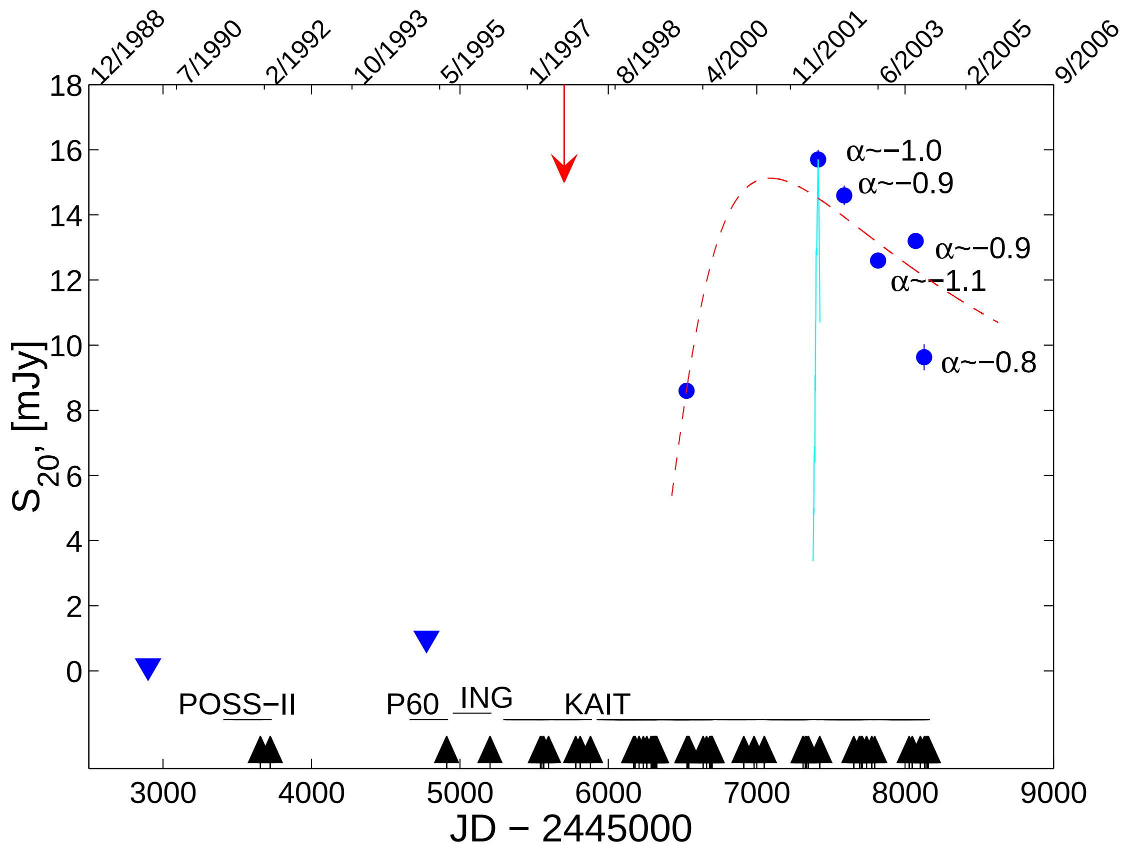

Fig. 1.— Radio (1.4 GHz) light curve of VLA121550.2+130654. Inverted triangles mark upper limits from archival VLA observations. Superposed are the radio light curves of two radio-bright events: SN 1979C (Type II; Weiler et al. 1991; dashed red curve) and SN 1998bw (Type Ic; Kulkarni et al. 1998; solid cyan curve). These were scaled in flux and shifted to match the approximate time of peak radio luminosity (see text). The light curve of VLA121550.2+130654 is quite similar to that of SN 1979C, and markedly different from that of SN 1998bw, suggesting a Type II identification for this event. The red arrow at the top of the figure marks the date of peak optical brightness of SN 1979C, relative to its peak 1.4 GHz radio flux. The bottom of the figure describes a search for a bright optical SN in NGC 4216 in archival images we have collected, obtained by the 30-inch KAIT, the Palomar 60-inch and 48-inch (POSS-II) telescopes, and the 1-m JKT telescope. The black arrows mark the dates of observations while the horizontal lines represent our estimate for the period of time in which an unobscured SN would have been visible in these archival data (see text). An optical counterpart to VLA121550.2+130654 is not detected in any of the images we inspected, suggesting that this event was heavily obscured by dust.

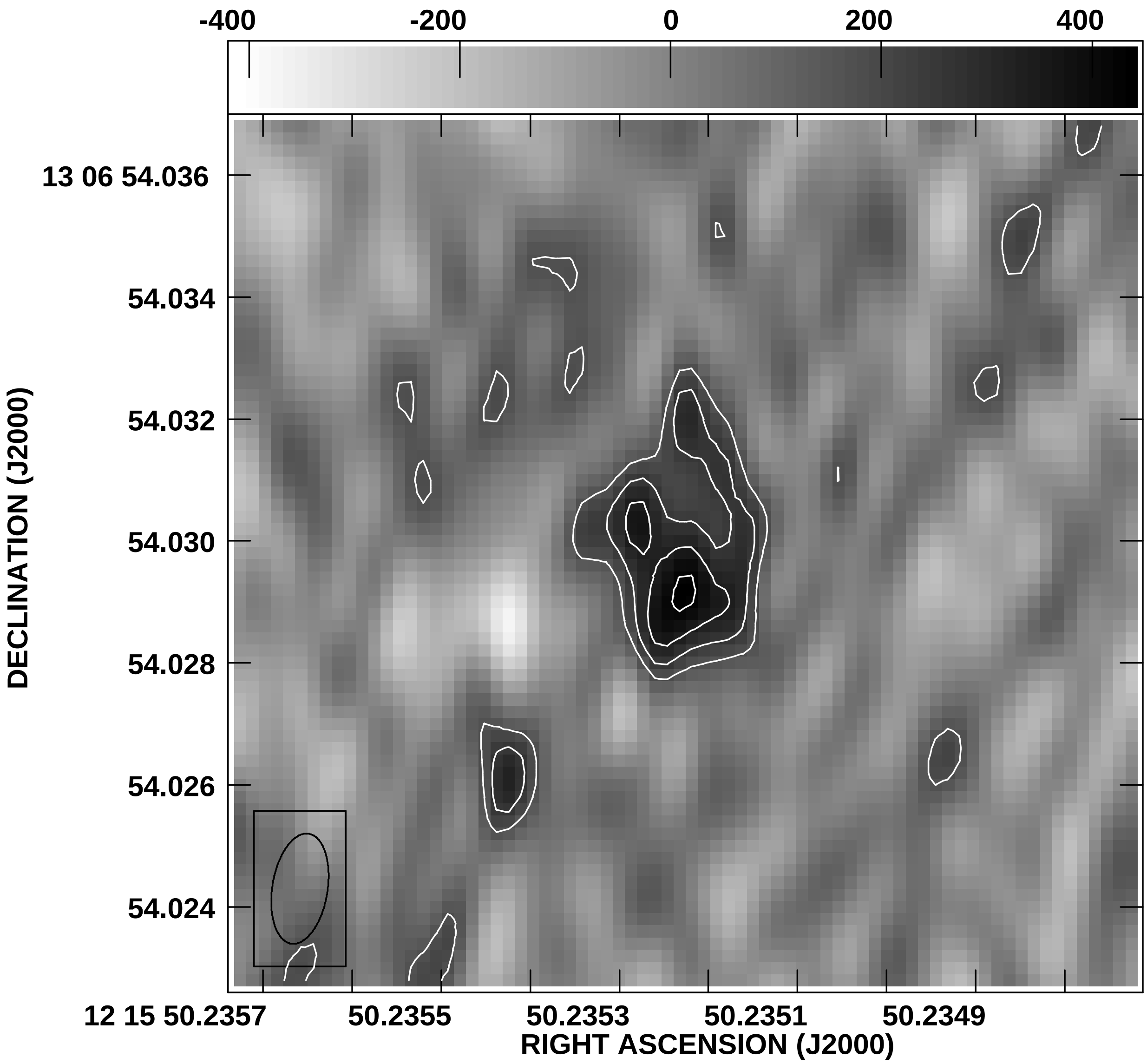

Fig. 2.— VLBA contour map of VLA121550.2+130654 at $t \approx 7$ years. At 8.5 GHz, the radio transient may be marginally resolved with a slightly asymmetric structure. Gaussian fitting yields size estimates that are comparable to the size of the synthesized beam, shown in the lower left-hand corner. We place a firm 3σ upper limit of 4.0 mas on the source size (see text). The greyscale intensity map spans from -408.3 to 436.4 μJy beam^{-1}. Contours represent flux in linear increments from 2σ to 10σ (84 to 840 μJy).

3.2. VLA172059.9+385227: A Radio Transient Source Without a Bright Optical Counterpart

Figure 3 shows the location of VLA172059.9+385227 on our deepest R-band image. The image astrometry was solved with respect to the USNO-A2.0 catalog (Monet et al. 2003) using 10 unsaturated stars, and has a root-mean-square (RMS) accuracy of $\sim 0.4''$. Cross-correlating the positions of 3300 sources within 10° from VLA172059.9+385227 which appear in both the FIRST and USNOA-2.0 catalogs, we derive the total uncertainty in placing FIRST sources (with similar flux to that of VLA172059.9+385227) on the USNOA-2.0 reference frame. This error includes both statistical uncertainties in the reported positions of cataloged sources, as well as any systematic deviations between the FIRST and USNOA-2.0 reference frames. We find the total uncertainty for this source to be $0.72''$ at the 1σ confidence level. Reassuringly, χ^2 analysis of the residuals shows that the systematic difference between the FIRST and USNO reference systems at this location must be small ($< 0.1''$). Accordingly, the radius of the circle marked on Figure 3 is $0.72''$, demonstrating that there is no galaxy detected in the vicinity of the radio source. The nearest galaxy (marked A in Fig. 3; total R-band magnitude ~ 24.5) is $\sim 3''$ away. We therefore determine that any point source or compact galaxy at the location of VLA172059.9+385227 must be fainter than $R = 24.5$ mag. Similar limits are obtained from our g-band and I-band observations. We cannot firmly rule out an association between VLA172059.9+385227 and nearby galaxies A, B, or C, since our ground-based imaging lacks the depth and resolution required to properly model the light distribution of these faint sources, and so determine how likely is the association of the radio source with these galaxies (as done, e.g., by Gal-Yam et al. 2003). However, the density of similar sources in our deep images suggests that chance coincidence is quite possible.

As shown in Paper I, the typical distance to an orphan radio afterglows detected in our survey, assuming our fiducial parameters, should be ≤ 140 Mpc ($z \approx 0.033$ for $H_0 = 70$ km s^{-1} Mpc^{-1}), and even under the most favorable assumptions these events should always be below $z \approx 0.2$. At that distance any possible host galaxy (either galaxy A or another undetected galaxy closer to the radio location) would have an absolute magnitude $M_R > -11$ for $z = 0.033$, or $M_R > -15.5$ for $z = 0.2$, i.e., be a very low luminosity dwarf (fainter, possibly much fainter, than the Small Magellanic Cloud). This leads us to conclude that this source is unlikely to have been an orphan radio GRB afterglow.

If not an orphan GRB afterglow, what is the nature of this source? We now briefly consider several alternatives. In principle, this could have been an on-axis GRB afterglow, as these are seen to great cosmological distances, and often reside in host galaxies which have very faint apparent optical magnitudes (e.g., Vreeswijk et al. 2001; Jaunsen et al.

2003; Berger et al. 2002; Berger et al. 2005, in prep.). However, the radio brightness of this transient (9.4 mJy) is unprecedented for on-axis GRBs; it is far brighter than every afterglow of cosmological GRBs observed to date (e.g., Frail et al. 2003). In addition, in paper I it is shown that the population of observed radio afterglows is always dominated by those that have become almost spherical. Thus, if this source is a distant beamed afterglow, we would have expected to see many other less-beamed afterglows, which we don't. We thus conclude that this source is unlikely to be associated with a GRB, either on-axis or off-axis.

This source could have been a radio flare from a peculiar AGN, perhaps an extreme and/or high-z analog of SDSS J124602.54+011318.8 (Gal-Yam et al. 2002). If that is the case, then during the flare caught by the FIRST observations, the radio loudness of this AGN was extremely high ($\Re > 10000$)[4].

Alternatively, we may have observed a radio flare from a Galactic object, perhaps similar to those recently reported by Hyman et al. (2005) and Bower et al. (2005). Possible sources for such transient flares are discussed by these authors, as well as by Kulkarni & Phinney (2005) and Turolla, Possenti, & Treves (2005). However, the high Galactic latitude of this source ($\sim 33°$) appears to disfavor this option.

Finally, since ours is the first wide-field survey for radio transients, we may have discovered a new type of object, yet to be characterized. To conclude, the exact identification of VLA172059.9+385227, the last event in our survey which we cannot yet securely associate with a known astrophysical source, remains somewhat of a mystery, and definitely merits further study. However, it appears that this source is not at low redshift, and is therefore unlikely to be a radio orphan GRB afterglow.

4. Discussion and Conclusions

4.1. Limits on the Typical Beaming of GRBs

In Paper I it has been shown that for a GRB population with a given isotropic equivalent burst energy, $E_{\rm iso}$, the number of orphan radio afterglows anticipated to be detected in a

[4]Following Stocke et al. (1992), we define the radio loudness $\Re$ as the ratio of the radio flux at 5 GHz to the optical B-band flux. We translate our R-band upper limit and 1.4 GHz radio flux to the Stocke et al. bands assuming a typical flat AGN spectral slope ($\alpha \approx 0.5$) and a source redshift $z < 3$. Assuming higher redshifts for the source would increase $\Re$, by up to an order of magnitude at $z = 5$. Assuming steeper spectral slopes would decrease $\Re$, by up to an order of magnitude for $\alpha = 1.6$, which is quite atypical for AGNs.

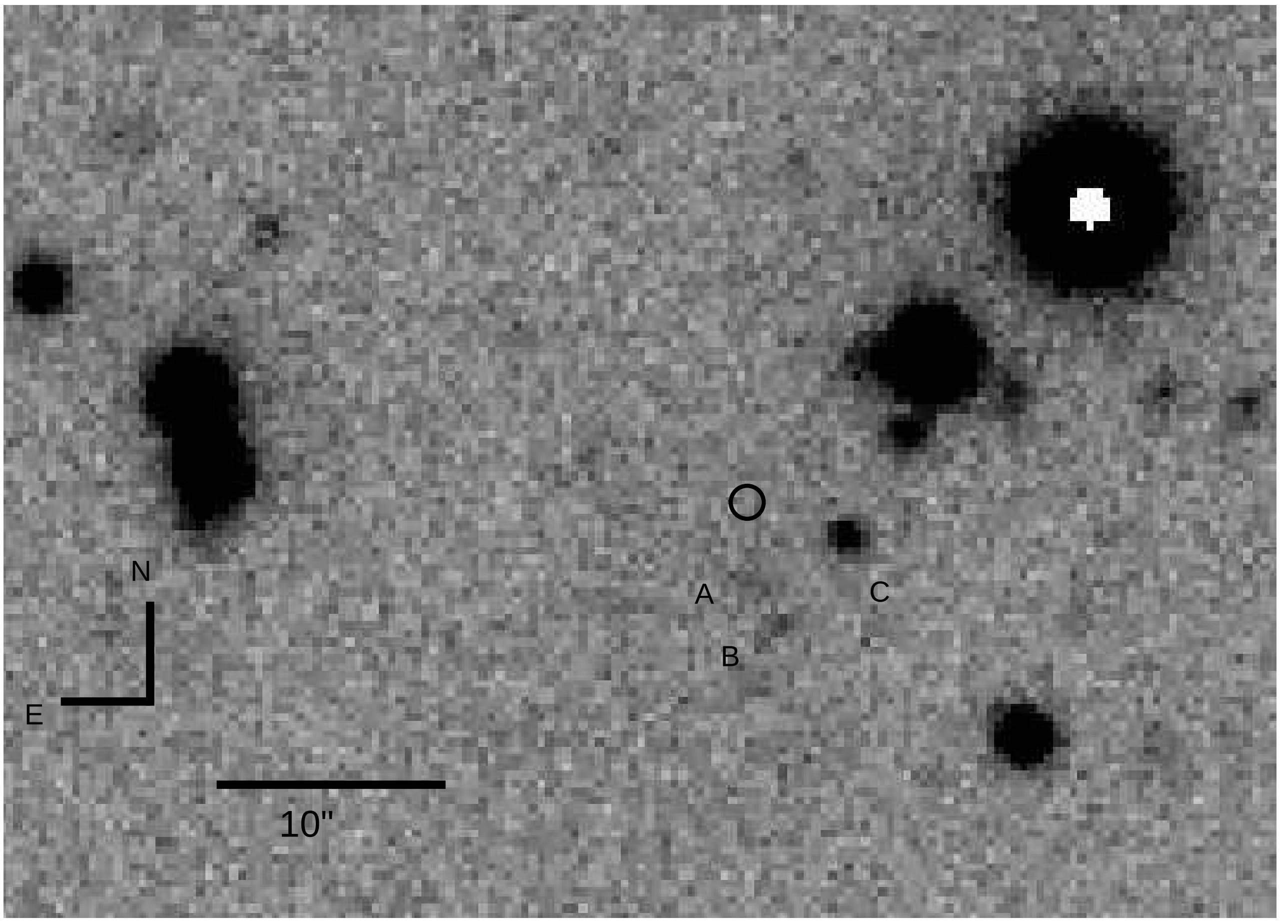

Fig. 3.— P200 R-band image of the location of VLA172059.9+385227. Nearby galaxies A ($R = 24.5 \pm 0.4$ mag) B ($R = 24.6 \pm 0.4$ mag) and C ($R = 23.5 \pm 0.4$ mag) are marked. The bright source due North-West is a star. The radio location is marked by the black circle, with $0.72''$ radius representing the 1σ positional uncertainty. The distance to the nearest detected galaxy (A) is $\sim 3''$. The faintness of all possible host galaxies argues against a low-z origin for VLA172059.9+385227, and therefore against it being an orphan radio GRB afterglow.

flux-limited survey is smaller for larger beaming factor f_b^{-1}, contrary to naive expectations (here $f_b \equiv \theta^2/2$, with θ being the opening angle of the GRB ejecta). Obviously, if the beaming factor is larger, more GRBs occur in nature, as the rate measured by earth-orbiting spacecraft represents a smaller fraction of the total population, most of which is beamed away from us. However, since the energy we measure is $E_{\rm iso}$, which is related to the true energy of the bursts by $E_b = f_b E_{\rm iso}$, a larger beaming factor implies that the typical burst is less energetic. This will cause the number of observed afterglows to be smaller for two reasons. First, a smaller true energy E_b implies a smaller luminosity distance below which the radio flux emitted by a source that has undergone a transition from relativistic to subrelativistic expansion exceeds some detection limit. Second, the time a source spends above the detection limit is shorter for a smaller E_b. In Paper I we have shown that these two effects combined overcome the expected increase in source counts due to the larger true GRB rate inferred from the observed rate for larger beaming factors.

For a flux threshold of 6 mJy, as in the present analysis, the maximum redshift below which sources are above the detection limit is $z \approx 0.2$ for $h = 0.75$ (Paper I; $H_0 = 100h$ km s^{-1} Mpc^{-1}), and so cosmological effects can be neglected. In this limit the number of radio orphans expected in a survey is proportional to $f_b^{5/6}$ (Paper I). Thus, the upper limit derived on the number of radio afterglow sources implies a lower limit on the beaming factor, f_b^{-1}. In Paper I we obtained $f_b^{-1} > 13$ at the 95% confidence limit (CL) using a complete subsample out of the 9 candidates that were identified there, a local GRB rate of $\dot{n} = 0.5$ Gpc^{-3} yr^{-1}, and our canonical choice of the remaining parameters. A recent analysis by Guetta, Piran, & Waxman (2005) yields a local GRB rate of $\dot{n} = 0.67(h/0.75)^3$ Gpc^{-3} yr^{-1}.

The rejection of all candidates by the follow-up observations described in this paper implies an upper limit of 65 all-sky radio afterglows above 6 mJy at 95% Poisson CL (see Paper I for further details). With this new upper limit, and using eq. (9) of Paper I, the modified lower limit on the beaming factor is

$$f_b^{-1} \geq 62 \left(\frac{\dot{n}}{0.67\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}} \right)^{6/5} \left(\frac{\epsilon_B}{0.03} \right)^{27/20} \left(\frac{\epsilon_e}{0.3} \right)^{9/10} \left(\frac{n}{0.1\ \mathrm{cm}^{-3}} \right)^{19/20} \left(\frac{\tilde{E}}{5 \times 10^{53}\ \mathrm{erg}} \right)^{11/5}, \tag{1}$$

where ϵ_B and ϵ_e are (respectively) the magnetic field and relativistic electron equipartition fractions, n is the density of the local ambient medium in which the blast wave propagates, and $\tilde{E} \equiv < E_{\rm iso}^{11/5} >^{5/11}$.

Model parameters are normalized in eq. (1) to values derived from afterglow observations. Values of close to equipartition, $\epsilon_e \geq 0.1$, are typically inferred from most optical afterglows, and from the clustering of explosion energies (Frail et al. 2001) and X-ray afterglow luminosity (Freedman & Waxman 2001; Berger, Kulkarni, & Frail 2003); $\tilde{E}$ is normalized to

the value $< E_{\gamma,\mathrm{iso}}^{11/5} >^{5/11} = 5\times10^{53}$ erg obtained for GRBs with known redshifts (Bloom et al. 2003), taking into account that while the GRB kinetic energy is likely several times larger than the γ-ray energy, the population of GRBs with known redshifts is probably brighter, on average, than the whole cosmological GRB population.

The values of n and ϵ_B are not as well determined by observations as the values of $\tilde{E}$ and ϵ_e. The reason is that they depend strongly on an observational parameter which is less well determined by afterglow observations: the self-absorption frequency ν_a. While $\tilde{E} \approx 1/\epsilon_e \approx \nu_a^{(5/6)}$, we have $n \approx \nu_a^{(25/6)}$, and $\epsilon_B \approx \nu_a^{(-5/2)}$. The value of ν_a is determined at best, in only a few cases, to within a factor of 2–3. Therefore, in most cases the uncertainty in determining n (and ϵ_B) is at least an order of magnitude. In cases where ϵ_B can be reliably constrained by multi-waveband spectra, values not far below equipartition are inferred (e.g., Frail, Waxman, & Kulkarni 2000). Our analysis depends on $\epsilon_B^{27/20} \times n^{19/20} \approx \nu_a^{7/12}$, so we are not so sensitive to the uncertainty in n and ϵ_B separately. As explained in Paper I, afterglow observations typically imply $\epsilon_B \times n \geq 10^{-3}$ cm^{-3}.

It should be emphasized, however, that the lower limit of eq. (1) is uncertain due to uncertainties in model parameters. Afterglow models are highly idealized and the values of model parameters are therefore accurate only to within a factor of a few. Nevertheless, this analysis provides a direct evidence for beaming in GRBs which is independent of that provided by afterglow light curves.

The lower limit directly imposed on $< f_b^{-1} >$ by our analysis is consistent with the value $< f_b^{-1} > = 75 \pm 25$ derived by Guetta et al. (2005). These authors compare the Frail et al. (2001) distribution of jet opening angles inferred from breaks in the afterglow light curves with model predictions applied to the BATSE GRB catalog, and their results are thus completely independent. This is encouraging and has two major implications. First, if this consistency is to be maintained, future deeper or wider radio surveys should detect many afterglows (§ 4.3). Second, while the values of ϵ_B and ϵ_e may be assumed universal, as they are determined by shock microphysics, n may vary significantly among bursts. Higher values for the typical ambient density ($n \approx 10$ cm^{-3}), as advocated by Bloom, Frail, & Kulkarni (2003), require low values of ϵ_B in order to reproduce afterglow observations (Paper I). A combination of large n and large ϵ_B would drive $< f_b^{-1} >$ to large values (eq. 1), resulting in a strong inconsistency with the analysis of Guetta et al. (2005). Recast in another way, requiring consistency between our results and the independent analysis of Guetta et al. (2005) could be taken as an indication that values of $\epsilon_B \times n/(0.01 \text{ cm}^{-3}) >> 1$ are ruled out.

Note that this analysis assumes no correlation between E_{iso} and the beaming fraction f_b, which is the most general assumption that can be made. Our results will be modified by factors of order a few if a correlation is assumed, depending on its exact form. For example,

if we assume the correlation derived by Frail et al. (2001), namely a constant $E_{\rm iso} \times f_b$, then we should replace $< E_{iso}^{11/6} >$ by $< E_{iso} >^{11/6}$ in eq. (9) of Paper I, resulting here in a modified lower limit $f_b^{-1} > 20$. In fact, this is the value that should be compared with the analysis of Guetta et al. (2005), which explicitly assumes the Frail et al. (2001) correlation. This agreement ($f_b^{-1} > 20$ compared to $f_b^{-1} >= 75 \pm 25$) shows that our above conclusions are supported also in this case.

4.2. An Upper Limit on the Total Rate of Relativistic Explosions

Little is known about the fraction of relativistic cosmic explosions that produce bright γ-ray radiation. Observationally, the existence of X-ray flashes (XRFs; Heise et al. 2001) and their association with Type Ib/c SNe (Soderberg et al. 2005b) suggests that the peak energy of such explosions can be at soft X-rays, or even in the very far ultraviolet, in which case they will be very difficult to detect. For example, a "dirty" fireball, with a Lorentz factor low enough so it is optically thick to γ-rays, will escape real time detection by orbiting γ-ray observatories (Rhoads 2003). However, all such explosions, regardless of the explosion geometry and the initial Lorentz factor (as long as it is $\gtrsim 2$), would produce similar late radio afterglows.

Adopting the parameters values of Paper I and our upper limit on the number of relativistic explosions (< 65 over the entire sky) we can write eq. (9) from Paper I as

$$\dot{n} \lesssim 1000 \times E_{0,51}^{-11/6} {\rm Gpc}^{-3}{\rm yr}^{-1}, \tag{2}$$

Where $E_{0,51}$ is the total energy in relativistic ejecta in units of 10^{51}erg, and the propagated confidence level from the upper limit on the number of explosion over the entire sky (65, § 1) is 95%. This rate is much smaller than the rate of core-collapse SNe ($r_{cc} \approx 7.5 \times 10^4$ Gpc^{-3}yr^{-1} at $< z >= 0.26$ and $\sim 1.9 \times 10^4$ Gpc^{-3}yr^{-1} at $z \approx 0$; Cappellaro et al. 1999, 2005) or the rate of Type Ib/c SNe which is ~ 0.2 of the total rate of core-collapse SNe. This implies that only a small fraction, a few per cent at most, of the the population of core-collapse SNe release a significant fraction of their explosion energy in the form of relativistic ejecta, as suggested by Berger et al. (2003) and Soderberg et al. (2005a) specifically for Type Ib/c events. Our findings therefore rule out unified models of GRBs, XRFs, and SNe Ib/c as viewing-angle dependent manifestations of relativistic conical jets (e.g., Lamb, Donaghy, & Graziani 2005). Alternative models, e.g., invoking ultra-relativistic "cannon balls" (Dar & De Rújula 2004), are not expected to produce bright late-time radio afterglows (Dar & Plaga 1999), and are therefore not constrained by our observations. Provided that the beaming fraction of GRBs

and XRFs is constrained by an independent measurement, future surveys for orphan GRBs may be able to pin down the total rate of relativistic explosions, compare it to the rate of GRBs and XRFs, and probe the existence of other types of relativistic explosions.

4.3. Implications for Future Radio Surveys

The follow-up observations reported here imply that the radio survey we reported in Paper I discovered four real variable sources: an AGN, a pulsar, a radio SN, and one unidentified, optically-faint, either Galactic or high-redshift source. As discussed in great detail in § 4.1 of Paper I, our survey effectively covered $\sim 1/17$ of the sky at the 6 mJy level. Our results therefore lead us to project that ~ 70 real sources would have been discovered in a similar all-sky survey. Obviously, more sensitive surveys will discover many more such events. For instance, assuming Euclidean space and no source evolution, we predict > 1000 variable sources in a similar survey with a detection limit of $F_{\rm limit} = 1$ mJy (since the number of sources is proportional to $F_{\rm limit}^{-\frac{3}{2}}$). Considering the fact that sources such as AGNs have steep luminosity functions (i.e., that there are many more faint than bright sources), this is probably a very conservative lower limit. Additionally, our search was restricted to truly transient sources (which are not detected at all in one of the epochs) while the number of strongly variable sources will be much larger. Therefore, forthcoming surveys by instruments like the Allan Telescope Array (ATA), and, in the more distant future, the Square Kilometer Array (SKA), are not only bound to discover many such events, but will have to account for this population as a source of systematic "noise" in many other types of studies.

Van Dyk et al. (2000) discuss the implications that a next-generation radio array (in that case, SKA) will have on *follow-up* observations of individual radio SNe. Let us discuss here the use of radio surveys with the ATA as a means to *discover* radio SNe.

The ATA is a new radio telescope array, operated jointly by the University of California, Berkeley (UCB) and the SETI institute, now under construction at UCB's Hat Creek radio observatory. The first radio dishes of the ATA are already in place, and the complete array, consisting of 350 6.1-m radio telescopes, is expected to be completed by the end of the decade. The full array will be able to cover the entire sky visible from Hat Creek (~ 30000 square degrees), down to a 5σ detection limit below 1 mJy at 1.4 GHz, in less than a week. For sources with variability time scales longer than a week (such as radio SNe), this is thus effectively a continuous survey.

Sources as luminous as VLA121550.2+130654 would be detected by the ATA in all galaxies closer than ~ 64 Mpc. Such a survey would therefore produce a full census of

nearby radio-bright SNe. This SN sample will have several unique properties. Since the discovery mode we discuss here is through an all-sky survey, the resulting sample will not depend on the properties of the host galaxies. In particular, this sample will be free from possible selection biases introduced by searching for SNe only in optically bright galaxies, as done by most of the successful optical searches responsible for discovering the majority of nearby SNe (e.g., the KAIT search at Lick Observatory; Filippenko 2005, and references therein). In addition, the background emission from host galaxies is expected to have little effect on SN discovery in the radio band, and thus the SN position within its host is expected to have little effect on its discovery, as opposed to optical searches which are less efficient near the bright nuclei of galaxies and in edge-on spirals. Finally, as demonstrated here, a radio-selected SN sample will be almost free from the effects of absorption by dust, which strongly affect searches in the optical and even in the infrared (see, e.g., Maiolino et al. 2002; Mannucci et al. 2003). Such a survey will still have a bias toward radio-bright SNe, and will need to account for the radio luminosity function of core-collapse SNe. Overall, though, it will provide a valuable addition to studies based on SN optical surveys.

The real revolution is expected with the advent of the sensitive SKA. The accumulated experience gathered in the last few years shows that *every* core-collapse SN closer than 10 Mpc, and certainly below 5 Mpc, is detectable in the radio with the VLA (Weiler et al. 2002; Berger et al. 2003). Put in other words, there are no "radio-quiet" SNe among nearby events, including those SN subtypes (e.g., SNe II-P) that have been considered to be radio-quiet in earlier literature[5]. The SKA is expected to be 100 times more sensitive than the VLA (Cordes, Lazio, & McLaughlin 2004), and so it should detect *every core-collapse SN* out to 50–100 Mpc. Thus, based on our current understanding of radio SNe, we expect the volume-limited sample of radio SNe discovered by an all-sky survey with the SKA will be indeed almost unbiased, free from the effects of dust, and will not depend on the radio luminosity function of SNe. Such a sample will probe the overall SN rate, a tracer of the local star-formation rate; the properties of SNe as a function of host-galaxy type, color, morphology, and luminosity; and the distribution of SNe within their hosts.

Finally, in the context of our initial motivation to conduct the study described in Paper I, all-sky variability surveys with telescopes like the ATA and SKA will be able to discover GRB radio afterglows, both from on-axis events (whether seen by high-energy satellites or not) and, if these events are indeed numerous, also from relatively nearby "orphan" afterglows.

[5]We emphasize this is true only for core-collapse events. SNe Ia, generally considered to result from thermonuclear explosions of white dwarf stars, have never been detected in the radio, and may well be genuinely radio-quiet.

4.4. Summary

We have presented follow-up radio and optical observations of candidate radio transients identified by comparing the FIRST and NVSS radio surveys in search for possible orphan radio afterglows of GRBs (Paper I). Our new observations allow us to characterize the nature of all of the previously discovered transients, which constitute a complete representative sample of radio transients down to 6 mJy a 1.4 GHz. We conclude that none of these sources is likely to have been an orphan GRB afterglow.

We use this fact to re-derive a lower limit on the beaming factor $f_b^{-1} \geq 62$ ($f_b^{-1} \geq 20$ assuming the Frail et al. 2001 correlation) consistent with an independent estimate by Guetta et al. (2005; $< f_b^{-1} >= 75 \pm 25$). We then argue that if this consistency is to be maintained, then wider and/or deeper variability surveys, such as those expected to be conducted with the ATA and SKA, should detect numerous orphan afterglows; otherwise (i.e., if no orphan afterglows are detected by such surveys) an analysis similar to ours would result in lower limits on f_b^{-1} which will greatly exceed the Guetta et al. (2005) estimates.

We show that our survey constrains the rate of relativistic explosions of all types, and implies that just a small fraction of core-collapse SNe (and Type Ib/c in particular) release unconfined (e.g., conical jets) of relativistic ejecta, the basic ingredient in fireball models of long-soft GRBs.

Our likely detection of an optically obscured radio SN in the Virgo spiral galaxy NGC 4216 illustrates the power of wide, sensitive, radio-variability surveys, such as those planned with the ATA and SKA, to uncover a population of hidden SNe, which currently escape detection even in the most nearby galaxies. Sensitive radio surveys may thus provide, for the first time, a complete census of core-collapse SNe, free from various selection biases which contaminate current compilations, such as the tendency to monitor (and discover) SNe only in bright, luminous galaxies, and the strong effects of host-galaxy dust obscuration on the discovery of SNe in optical surveys.

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Table 1. Flux Measurements of Candidate Radio Transients

#	Candidate	Data source	UT Date	1.4 GHz Flux [mJy][a]
1	VLA082150.2+174616	NVSS	Nov. 1, 1993	Confused with sidelobes from nearby 1.8 Jy source
		FIRST	Jan. 1998	5.3
		This work	Nov. 11, 2002	5.0 ± 0.8
2	VLA104848.9+551509	NVSS	Nov. 23, 1993	Missed due to blending with a nearby diffuse source
		FIRST	Mar. 1997	5.2 ± 0.16
		This work	May. 18, 2002	5.75 ± 0.15
		This work	Nov. 11, 2002	6.0 ± 0.3
3	VLA114355.3+221020	NVSS	Dec. 6, 1993	Confused with sidelobes from nearby 2.9 Jy source
		FIRST	Sep. 1998	5.4
		This work	May. 18, 2002	4.6 ± 1.1
		This work	Nov. 11, 2002	8.4 ± 1.8
4	VLA121550.2+130654	NVSS	Feb. 27, 1995	Undetected (≤ 1)
		FIRST	Dec. 1999	8.6 ± 0.2
		This work	May. 18, 2002	15.7 ± 0.3
		This work	Nov. 11, 2002	14.6 ± 0.3
		This work	Jun. 27, 2003	12.6 ± 0.2
		This work	Mar. 06, 2004	13.2 ± 0.2
5	VLA122532.6+122501	NVSS	Feb. 27, 1995	1 ± 0.9
		FIRST	Apr. 2001	6.45 ± 0.15
		This work	Nov. 11, 2002	6.34 ± 0.6[b]
6	VLA130713.5-052709	NVSS	Feb. 27, 1995	0.1 ± 0.4
		FIRST	Apr. 2001	5.3[c]
		This work	Nov. 11, 2002	-0.09 ± 0.16[d]
7	VLA152248.7+542644	NVSS	Nov. 23, 1993	1.8 ± 0.5
		FIRST	May. 1997	6.1
		This work	Nov. 11, 2002	7.7 ± 0.5[e]
8	VLA165203.1+265140	NVSS	Apr. 16, 1995	-0.1 ± 0.5
		FIRST	Dec. 17, 1995	5.3 ± 0.15
		This work	Oct. 18, 2002	0.7 ± 0.2
		This work	Nov. 11, 2002	0.5 ± 0.2[f]
9	VLA172059.9+385227	NVSS	Apr. 19, 1995	-0.9 ± 0.5
		FIRST	Aug. 7, 1994	9.4 ± 0.2[g]
		This work	Oct. 18, 2002	Undetected (-0.07 ± 0.1)
		This work	Nov. 11, 2002	Undetected (0.01 ± 0.1)[h]

[a] We have remeasured the flux in archival FIRST data, and report here our revised measurements, which are slightly different (typically by less than 10%) from those reported in the FIRST catalog and used in Paper I.

[b] An X-band flux of 4.76 ± 0.05 mJy measured on the same date indicates a flat spectrum with power-law index $\alpha = -0.16$ (where $F_\nu \propto \nu^\alpha$).

[c] Nearby unusual negative-flux features and unexplained elevated noise levels cast doubt on the reality of this detection.

[d] Undetected also in contemporaneous X-band measurements (-0.02 ± 0.05 mJy).

[e] Measurements of this source are compromised by a combination of a nearby source with similar flux which is not well resolved by NVSS, and elevated noise levels from a 1.3 Jy source just $13'$ away. Comparing our best reduction of the higher-resolution data (FIRST vs. our own observations) we find that this source is most likely constant.

[f] Known radio pulsar PSR J1652+2651.

[g]In this case FIRST data were obtained prior to NVSS data.

[h]Similar limits are obtained at X-band. Other sources in the VLA field are constant.

Table 2. Radio Observations of VLA 121550.2+130654

Epoch (UT)	Frequency (GHz)	Flux Density (mJy)	RMS (mJy)	Array Config.
1990 Jan. 07	1.43	<0.15	···	D
1995 Feb. 27	1.43	<1.0	···	D (NVSS)
1999 Dec.	1.43	8.6	0.2	B (FIRST)
2002 May 19	1.43	15.7	0.3	BnA
2002 May 19	8.46	2.60	0.06	BnA
2002 Nov. 11	1.43	14.6	0.3	C
2002 Nov. 11	8.46	2.93	0.04	C
2003 Jun. 27	1.43	12.6	0.2	A
2003 Jun. 30	4.86	4.99	0.06	A
2003 Jun. 30	8.46	2.76	0.05	A
2003 Aug. 25	8.46	2.88	0.07	A
2004 Mar. 06	1.43	13.2	0.2	C
2004 Mar. 06	8.46	2.89	0.04	C
2004 May. 02	1.43	9.63	0.4	VLBA
2004 May. 02	8.46	2.5	0.5	VLBA

Note. — The columns (left to right) are (1) the UT date of each observation, (2) observing frequency, (3) flux density at the position of the radio transient, (4) RMS noise calculated from each image, and (5) VLA array configuration.

Table 3. Optical Observations of the Location of VLA172059.9+385227

UT Date	Telescope	Camera	Exposure times and filters
2003 Aug. 8	Wise 1m	Tektronics 1024^2 CCD	150 s V, 150 s R, 150 s I
2003 Mar. 7	P200	LFC	600 s R
2003 Jun. 28	P200	LFC	1200 s R
2004 Apr. 22	Keck I	LRIS R+B	300 s g, 300 s I
2004 Nov. 4	P60	2048^2 CCD	900 s g, 900 s R, 900 s I